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# Heavy quark production: recent developments

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**Abstract.** I discuss some aspects of the comparison between QCD predictions and experimental data in charm and bottom production.

Experimental information on the production of heavy-flavoured hadrons is impressive. Charmed hadron production has been studied extensively in fixed-target experiments, while colliders have provided a detailed picture of the productions of  $b$ -flavoured hadrons. Many aspects of the heavy-flavour physics have been studied in  $e^+e^-$  collisions at LEP. Recently, the discovery of the top quark at the Tevatron has opened the way to a new set of tests of the heavy-quark production dynamics. From the theoretical point of view, the production cross section for heavy quarks has been computed in QCD up to next-to-leading order, and detailed phenomenological analyses have been performed. I will not attempt here a summary of the results obtained in this field; a recent review of theoretical and experimental results and a complete bibliography is given in [1]. In the following, I will illustrate a few interesting issues which are currently under investigation.

I begin by considering first fixed-target hadro- and photo-production of charmed mesons. Comparisons between QCD predictions and data for the production of charmed particles are clearly very difficult, because the value of the charm quark mass, which sets the scale relevant for the production mechanism, is very close to the region where the applicability of perturbation theory becomes questionable. This said, one finds that at fixed-target energies,  $\sqrt{s} = 20$  to  $40$  GeV, the agreement between NLO QCD predictions and experimental data is in general satisfactory. Hadroproduction total cross sections are predicted with an uncertainty of about one order of magnitude, due to the large error coming from truncating the perturbative series at such low energies. The prediction is also very sensitive to the value of the charm mass. The experimental uncertainties are much smaller, and hadroproduction data are compatible with a charm mass of  $1.5$  GeV. The situation is much more favourable in the case of photoproduction, where theoretical uncertainties are much smaller; in this case, unfortunately, some of the experimental data are incompatible with one another, and it will not be possible to use these data to

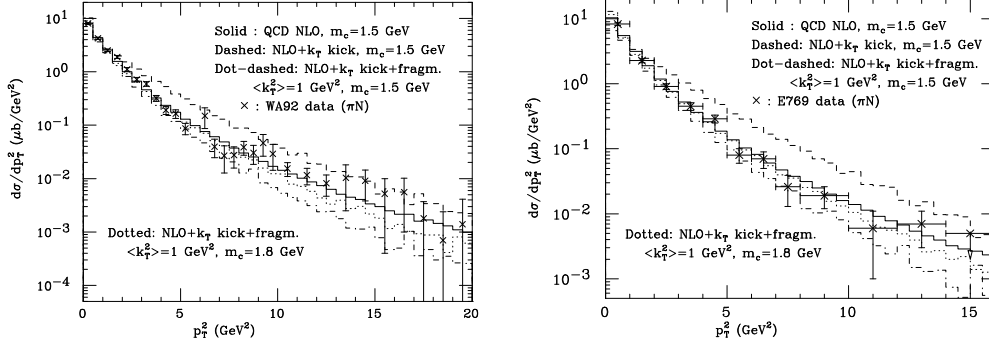


FIGURE 1.

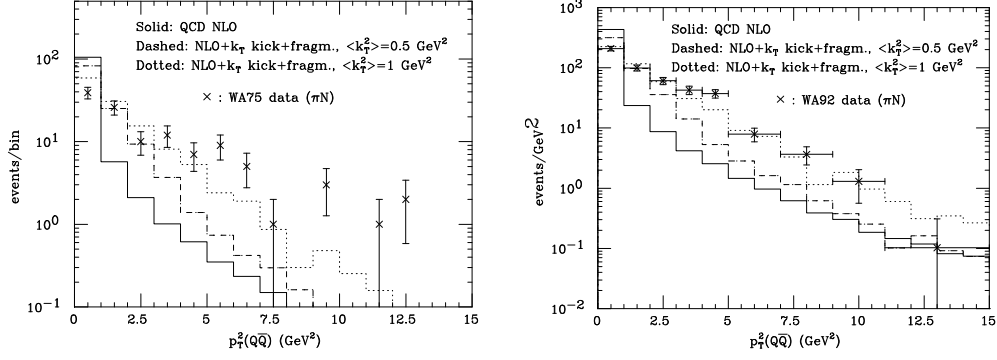
The single-inclusive  $p_T^2$  distribution measured by WA92 (left) and E769 (right), compared to NLO QCD predictions, with and without the inclusion of non-perturbative effects.

put constraints on physical parameters until these discrepancies are resolved.

When distributions are considered, it is necessary to take into account also non-perturbative effects, like the hadronization mechanism and the transverse momentum of partons in the colliding hadron beams. A comparison between QCD predictions and data for transverse quantities, like the transverse momentum spectrum of charmed hadrons, shows a reasonable qualitative agreement (see fig. 1, where experimental data from [2,3] and QCD predictions are shown). Longitudinal quantities are more difficult to predict reliably in a perturbative context, and other non-perturbative effects (like for example color dragging) must be taken into account. Also in this case, photoproduction data show a better agreement with QCD.

Some measurements of double differential distributions, like the azimuthal distance  $\Delta\phi$  between the charmed hadrons, or the pair transverse momentum, have been performed by fixed-target experiments [4,5]. The experimental results for azimuthal  $c\bar{c}$  correlations in hadron-hadron collisions show a tendency to peak in the back-to-back region  $\Delta\phi = \pi$ , but the peak is less pronounced than the one predicted by perturbative QCD. The addition of an intrinsic transverse momentum of the incoming partons gives a satisfactory description of the data. The data on the  $p_T^2(Q\bar{Q})$  distribution do not allow a unique interpretation. The theoretical prediction is in rough agreement with the WA92 measurement, and it is sizeably softer than the WA75 data, as shown in fig. 2

Experiments at the  $ep$  collider HERA have also collected data on heavy quark production. At HERA, the center-of mass energy of the photon-proton system is around 200 GeV; at these energies, the so-called hadronic (or resolved) photon component of the cross section can become relevant. In fig. 3 I present experimental data for the photoproduction cross section of charm as a function of  $\sqrt{s}$ . Both fixed-target and HERA data are shown. Theoretical predictions, obtained with two different parametrization of photon parton densities, are also displayed, together with the corresponding uncertainties.

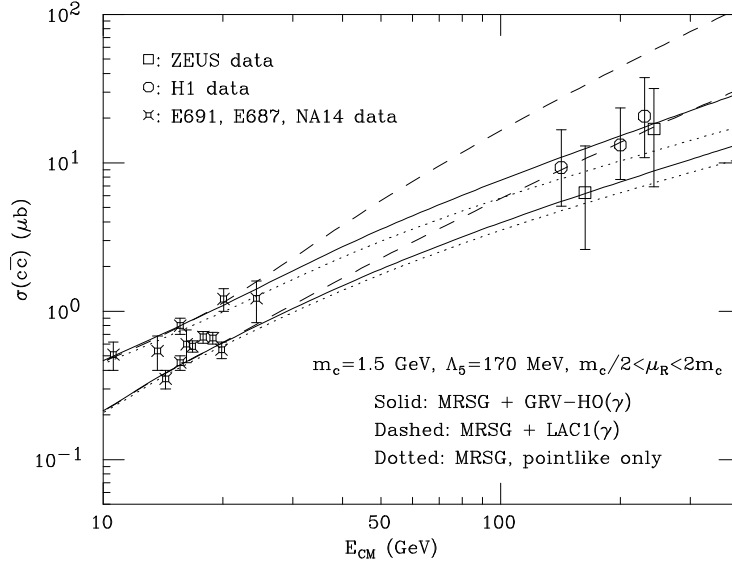


**FIGURE 2.**

NLO QCD result for the  $p_T^2(Q\bar{Q})$  supplemented with an intrinsic transverse momentum for the incoming partons, compared with the WA75 (left) and WA92 (right) data.

Observe that the HERA and fixed-target data are in good agreement with theoretical expectations. Improvement of the statistics of the HERA data, and the resolution of the discrepancies among fixed-target data I mentioned above, will probably allow to use total cross section data to put constraints on photon parton densities.

HERA data on distributions and correlations are still at a premature stage, and a significant comparison with theory will be possible when more statistics will be collected. It is worthwhile mentioning that a direct measurement of the gluon density in the proton using charm production is in principle possible



**FIGURE 3.**

Total cross section for the photoproduction of  $c\bar{c}$  pairs, as a function of the  $\gamma p$  center-of-mass energy: next-to-leading order QCD predictions versus experimental results.

at HERA [6].

Heavy-flavour production in high-energy hadronic collisions offers a good opportunity for QCD tests. For example, the  $b$  quarks produced at large  $p_T$  can be studied in perturbative QCD with smaller contamination from non-perturbative effects, with respect to charm. The problem of the  $b$  transverse momentum spectrum is a long-standing one. The first measurements were performed by the UA1 collaboration, while more recently the same distribution has been measured at the Tevatron by CDF and D0, whose results are shown in fig. 4. The situation can be summarized as follows. There is good agreement

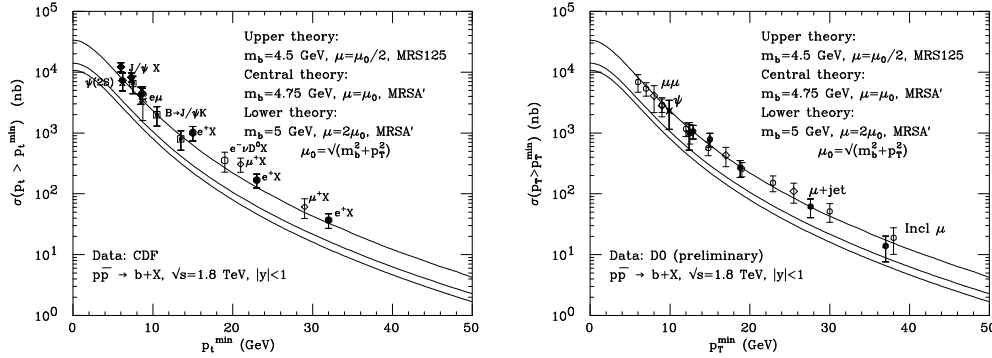


FIGURE 4.

CDF and D0 data on the integrated  $b$ -quark  $p_T$  distribution, compared to the results of NLO QCD.

between the shape of the  $b$ -quark  $p_T$  distribution predicted by NLO QCD and that observed in the data for central rapidities; although the data are higher by a factor of approximately 2 with respect to the theoretical prediction with the default choice of parameters, extreme (although acceptable) choices of  $\Lambda^{\overline{MS}}$  and of renormalization and factorization scales bring the theory in perfect agreement with the data of UA1 (not shown) and D0, and within 30% of the CDF measurements. The choice of low values of the scales is favoured by studies of higher-order logarithmic corrections. The CDF measurements at 630 and 1800 GeV indicate that theory correctly predicts the scaling of the differential  $p_T$  distribution between 630 and 1800 GeV, a fact that had often been questioned in the past and now finds strong support.

Forward production of  $b$  quarks indicates a larger discrepancy between theory and data, and more theoretical studies should be devoted to the understanding of the non-perturbative fragmentation function for heavy quarks. The standard Peterson parametrization may not be accurate enough for the description of the hadroproduction data.

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